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Research Article

Seismic Performances of Replaceable Steel Connection with Low Yield Point Metal

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Compared with the traditional steel rigid connection, the beam-column connections with weakened beam end have better ductility, but the local buckling in the weakened zone and the overall lateral deformation may occur in strong earthquake. The replaceable steel connection with low yield point metal is proposed based on the concept of earthquake resilient structure. In this connection, the weakened parts in the flange slab and web plate are filled with low yield point metal, and the metal firstly yields and dissipates energy sufficiently in earthquake; hence, the main parts are intact and the yield point metal can be replaced. The seismic performances of the three types of connections which include traditional connection, beam end weakened connection, and replaceable connection with low yield point steel under low cycle reciprocating load are studied. In addition, the energy dissipation capacity and damage characteristics of different connections are compared. The multiscale finite element models for the steel frames with different connections are analyzed by time-history method; both the computational efficiency and the accuracy are assured. The analysis results approve that the replaceable connection can confine the major damage in the replacement material and have better energy dissipation ability, safety reserves, and resilient ability.

1. Introduction

Steel frames are commonly used in multistory and high-rise buildings. In seismic design and maintenance of steel frames, the construction form and energy dissipation capacity of the beam-column connections are important and directly affect the safety and reliability of the total steel structures. At present, the usual type of beam-column connection is column-through and the typical forms of rigid beam-column connection include steel beam flange welded with column, web plate welded with column, or high-strength bolts connection. In early design of steel connection, it is assumed that the steel flanges bear all the bending moments and beam web plates only withstand the total shear force. However, the flexible capacity of this type of connection occupies only about 80% of the total value of the beam, which violates the basic principles of "strong node-weak component" in seismic design.

In Northridge earthquake which occurred in 1994 and Kobe earthquake which occurred in 1995, brittle fractures and extensive nonrepairable damage appeared in the traditional rigid beam-column connections of more than one hundred multistory and high-rise steel frames, which warned the designer that the traditional design could not fully achieve the desired seismic design requirements. Researchers studied various damaged structures following the above earthquakes and concluded that there was only rare evidence of plastic zones which were formed on the beams. Therefore, researchers proposed various improved methods, in which the plastic hinge offset method became a focus topic [1, 2]. The plastic hinge offset method aims to offset the stress concentration of the beam outward from connection nearby in order to avoid brittle fracture and includes two ways which are weakened on beam end and strengthened on beam end.

The idea of weakened beams was developed in the last decade, based on the design technique of trimming away steel parts from the region adjacent to the column connection without reducing dramatically the beams' load bearing capacity [1–4]. Dog-bone connection and web opening connection are the typical types of the weakened beam connection [5], and both types are realized by weakening the flange or the web on the steel beam in order to overcome the initial defect that the plastic zone is small and to oversize the length of plastic hinges so as to dissipate energy sufficiently in earthquake and realize the ductility design. Weakening the beam instead of reinforcing the connections has proved to be more economical, as while reducing the cross-sectional properties, the demand in panel zone and achievement of strong column and weak beam requirements has been minimized [6–11].

However, beam weakened connection has the following deficiencies. First, the integral stiffness of the component will decrease once the flange or the web is weakened, and security risks will occur if the design scheme is inadequate. Secondly, the serious accumulated plastic strain and damage will exist in severe earthquake and severe flexion and lateral deformation will occur, and the beam maybe completely ruptures if there are some aftershocks. In addition, the renovation technology of the weakened type connection is complex and the construction cost is high. Hence, it is necessary to develop new connection forms with more safety and reliability in order to realize performance based seismic design. In recent years, the conception about resilient structures emerged and develops continuously [12, 13]. Resilient structures refer to the structure which can regain the original function without repair or with simple retrofitting after earthquake, and there are several implementation methods for different structural style. Practical applications of the resilient steel structure are rare because of the complexity of structural design and construction technology, and the research on the replaceable steel components for severe damage is also less. Chou has proposed steel reduced flange plates (RFPs) to connect steel beam flanges and the column without any other direct connection [14]. Since the RFP connection is designed as strong column-strong beam-weak RFPs, the RFP functions as a structural fuse that eliminates weld fractures and beam buckling. Farrokhi has improved the form by drilling holes at cover plates to create an intentional weak point [15]. The deficiency of this approach is that the RFPs and the damaged beam parts are difficult to be replaced after a severe earthquake. Castiglioni et al. [16], Calado et al. [17], and Shen et al. [18] developed new types of seismic resistant composite steel frames with dissipative fuses, respectively. In case of strong seismic events, damage will concentrate only in these fuses. The deficiency of fuse method is that the beams are usually cut off so the redundant capacity may be inadequate once the fused are destroyed in the mainshock and the aftershocks occur frequently.

In view of the backgrounds above, a new type of replaceable steel beam-column connection with low yield point metal is proposed in order to overcome current deficiencies of the beam end weakened steel connection. In this new connection, the weakened parts in the flange slab and web plate are filled with low yield point metal, and the low yield point metal firstly yields and dissipates energy sufficiently in earthquake; thus the integral seismic performance is improved. In addition, the cumulative plastic deformation can be confined in the zone of the low yield point metal through rational design for the filling size, and the large deformation in the beam is avoided. The retrofitting of the connection after the earthquake is quick and convenient, which embodies the idea of resilient structures [19, 20].

The insightful information about the connection properties can be obtained from the quasistatic hysteretic curves and the finite element simulation analysis, especially for the performance evaluation and comparison for different types of steel beam-column connections. Meantime, the performance and dynamic characteristics of the total frame need to be taken into account also. Limited by the difficulty and the cost of the experiment about the global steel frame, the dynamic responses of the total steel frame are usually studied by nonlinear dynamic analysis methods. The most commonly used nonlinear analysis methods include global analysis based on macroelements and local analysis based on solid elements [21, 22]. Macroscopic model mainly uses the elements such as beams and shells; the computational complexity is less while the microscopic mechanism and damage phenomena such as local buckling, partial damage, and contact problem cannot be revealed. On the other hand, the finite analysis based on solid elements can simulate the partial destruction process but the computational amount is large and the nonconvergence may occurs for buckling simulation, so it is not suitable for the design and analysis for complex steel frames.

Multiscale model analysis focuses on simulating the different mechanical behavior in different scales with different levels of elements simultaneously and then combining the elements into a multiscale finite element model. Hence, the multiscale analysis may establish a balance point between accuracy and computational cost. In recent years, there are extensive studies on the multiscale analysis using the connection interface, constraints setting, and other issues; the multiscale analysis on the static and dynamic characteristics of engineering structures is carried out, and the validity and the accuracy are verified [23].

In this paper, the low yield point steel LY160 and composition metal Zn-22Al are selected as the replaceable metals for the new connection and the appropriate material constitutive curves are obtained through the material performance tests. The seismic performances of the three types of connections which include traditional connection, beam end weakened connection, and replaceable connection are studied with low cycle quasistatic simulation, and the energy dissipation capacity and damage characteristics of different connections are compared. At last, the multiscale finite element models for steel frames with different connections are analyzed by inelastic time-history method. The superiority of replaceable connection for seismic damping is verified.

2. Replaceable Steel Connection with Low Yield Point Metal

The common beam end weakened connection includes beam end flange weakened type and beam web plate weakened type, and the specific construction details are shown in Figure 1. The weakened parameters for flange slab can be determined according to the corresponding study of [3, 4]. b_f and h_b are assumed as the flange width and the cross section height of

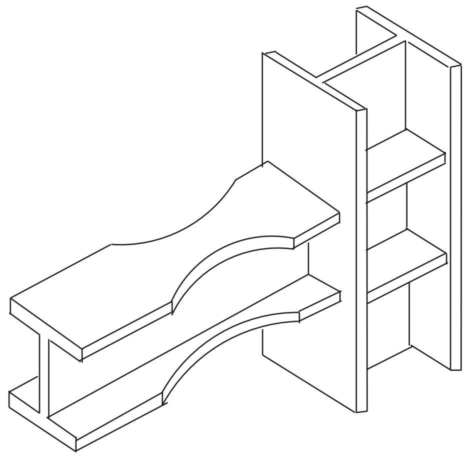
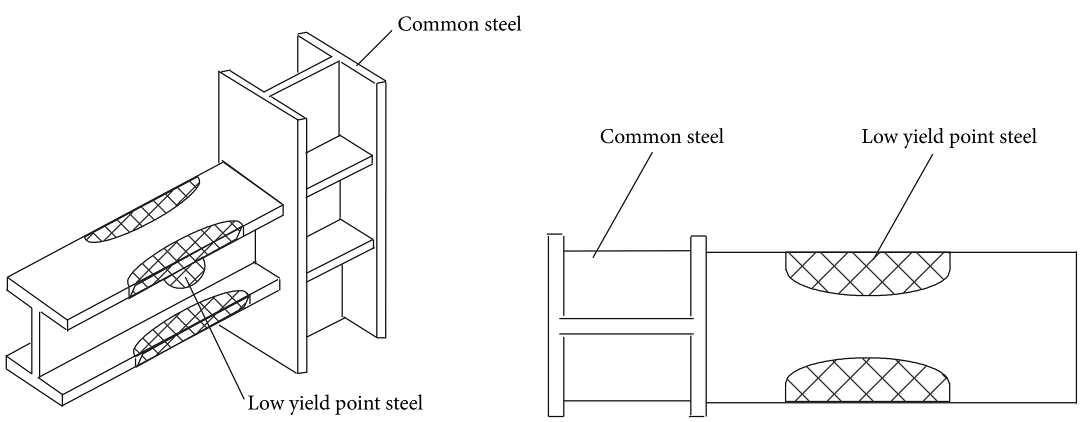

(a) (b)

Figure 1: (a) Flange slab weakened steel connection and (b) web plate groove weakened steel connection.



(a) (b)

Figure 2: (a) Side view of beam end weakened replaceable connection and (b) top view of connection.

the beam, respectively, and the distance a from the starting point of weakened zone to the column is set as $0.50\,b_f$~$0.75\,b_f$. The weakened length b is $0.65\,h_b$~$0.85\,h_b$, and the weakened depth c is $0.20\,b_f$~$0.25\,b_f$; the radius of the hole R is $0.25\,h_b$~$0.375\,h_b$.

To avoid the deficiencies of beam weakened connection, such as partial serious buckling in the weakened parts and lateral deformation in integral beam in strong earthquake, a replaceable beam-column connection with low yield point metal on beam end is presented, and the construction plan is shown as Figure 2. This new type connection evolves from the original beam end weakened connection, and the flange and the web are weakened by cutting corresponding parts simultaneously, but the low yield point mental is subsequently added on the weakened parts by welding or chemical bonding, in order to achieve better bearing capacity, damping, and ductility.

To utilize damping and energy-dissipated capacity entirely, the weakened size of the replaceable connection is advised to select the maximum value of the traditional weakened connection. The low yield point metal will constantly deform and firstly yields in earthquake and then the plastic hinges will occur on the weakened parts and the energy will be dissipated constantly, while serious plastic deformation will not emerge on the original part of the connection and the total seismic performance is ensured. After the mainshock, the damaged low yield point metal can be quickly replaced so that the overall seismic performance has been restored; hence, the steel connection and overall steel frame have the ability to resist aftershocks, and the conception about resilient structure can be realized finally.

3. Material Performances of Low Yield Point Metals

One of the key technologies of dissipating energy of the weaken connection is to select the metal material which has lower yield strength and extensibility. The damping of vibration in an earthquake with low yield point metals is theoretically studied by many researchers, but the effective experiments and engineering applications are less because the engineering requirement for the low yield point metal is strict.

In this study, steel LY160 and composition metal Zn-22Al are selected as the low yield point metals. The yield stress of steel LY160 is about 160 MPa, and it is verified that steel LY160 and the similar steel with low yield point have superior energy-dissipation capacity and it is suitable to be used as damping devices and members in building structures. Zn-22Al is made in aluminum in 22 percent, zinc in nearly 77 percent, and marginal iron and silicon, measuring as mass. Zn-22Al is made by casting method in steelworks, and then the metal blanks are subjected to heat treatment and are formed by cold rolling technique. Recent research on the material properties of composition metal indicates that Zn-22Al also has attractive ductility, and it has the latent capacity in vibration damping.

In order to measure and compare the actual properties of different metals, four materials including steel LY160, alloy Zn-22Al, carbon structural steel Q345 whose yield point is about 345 MPa, and steel Q235 whose yield point is about 235 MPa are manufactured as four groups of specimens with the same dimensions, respectively, for tensile test, and each group has three specimens. The average measured value of each group is viewed as the final results. It is worth noting that steel Q345 and steel Q235 are produced in China and the equivalent steel in ASTM standard is A572 and A36, respectively.

The standard specimen shape and size are shown in Figure 3. The specimen in tensile state and fracture state is shown in Figures 4 and 5, respectively. The average constitutive curves of four types of specimens are shown in Figure 6. It can be seen that the respective measured yield strength of steel Q345, steel Q235, steel LY160, and alloy Zn-22Al is 385 MPa, 275 MPa, 160 MPa, and 148 MPa. The measured extensibility is 23%, 27%, 31%, and 24%, respectively.

It is evident that both the steel LY160 and the alloy Zn-22Al have low yield point, superior ductility, and toughness; both metals can yield earlier than the normal carbon steels and fully dissipate energy at large deformation stage. The stability and the bearing capacity of the structure can be ensured if the proportion of the low yield point metal is reasonably proposed. Hence, the seismic behavior of the replaceable connections with the two types of metals is studied in this paper.

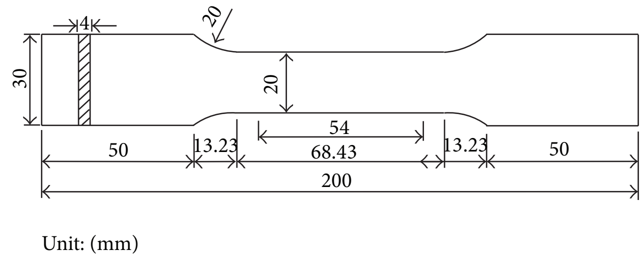


Figure 3: Specimen size.

Figure 4: Tensile test on site.

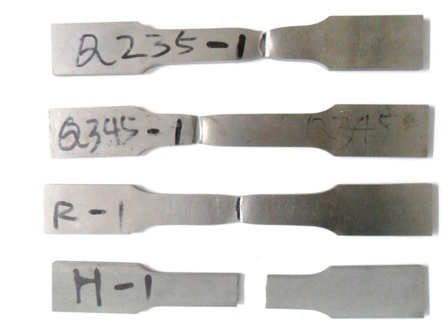


Figure 5: Fracture morphology.

4. Replaceable Steel Connection Seismic Performance Simulations

In order to validate the seismic performance of replaceable steel connection with low yield point metal, four models which include traditional connection, beam end weakened connection, replaceable connection with steel LY160, and replaceable connection with alloy Zn-22Al are established using FEM software ANSYS, based on the measured constitutive relationships [24]. All the models are analyzed with the low cyclic loading by nonlinear analysis, and therefore the hysteretic energy dissipation capacities of the four connections are studied and compared.

H-shaped steel is used as the section steel of the beams and the columns on the connections, and the main material is steel Q345. The cross-sectional dimension of the columns is 450 mm × 300 mm × 20 mm × 12 mm, and the cross-sectional dimension of the beams is 400 mm × 200 mm × 12 mm × 12 mm. Steel LY160 and alloy Zn-22Al are adopted as low yield point metal. The size parameters of weakened connection are chosen as the median value in the value range as mentioned above, and the details are listed in Table 1. Meanwhile, three different sizes are chosen for replaceable connections in order to evaluate the effect of the replaceable size on the structural seismic performance, and the parameters are also shown in Table 1.

The two ends of each column are fixed, and cyclical static load is applied on the end of the beams. The loading is

Table 1: Weakened and replacement size (unit: mm).

Connections	Parameters				
	Material	a	b	c	R
Beam weakened connection	Q345	125	280	45	125
Replaceable connection 1	Q345 and LY160	100	260	40	100
Replaceable connection 2	Q345 and LY160	125	280	45	125
Replaceable connection 3	Q345 and LY160	100	340	50	150
Replaceable connection 4	Q345 and Zn-22Al	125	280	45	125

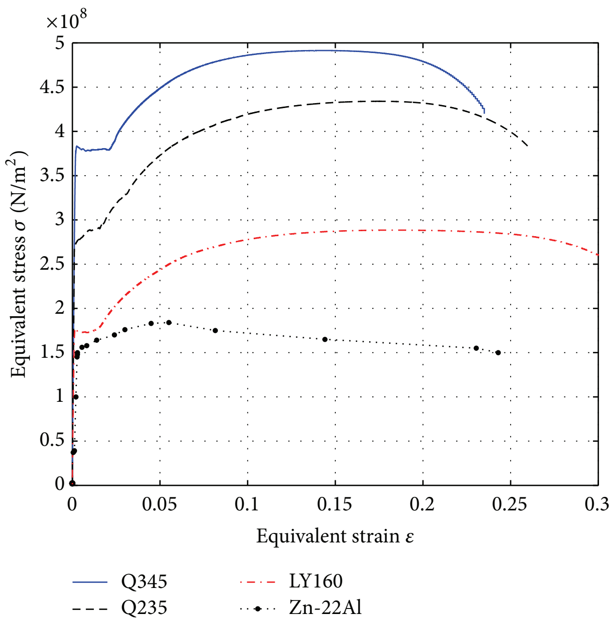


Figure 6: Constitutive curves of different metals.

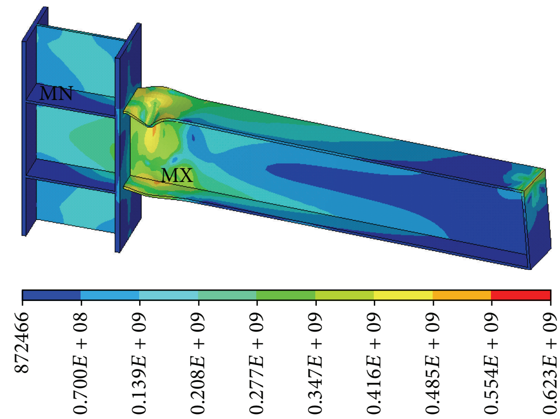


Figure 7: Stress of traditional beam-column connection.

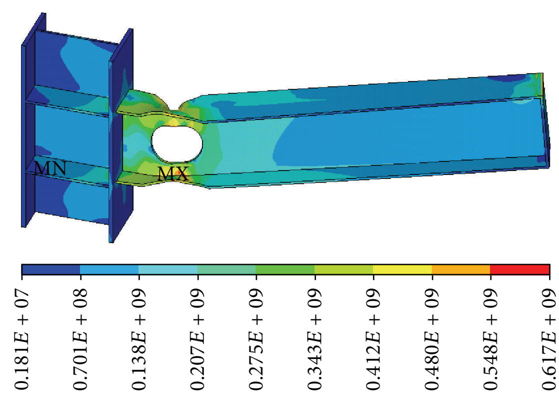


Figure 8: Stress of beam weakened connection.

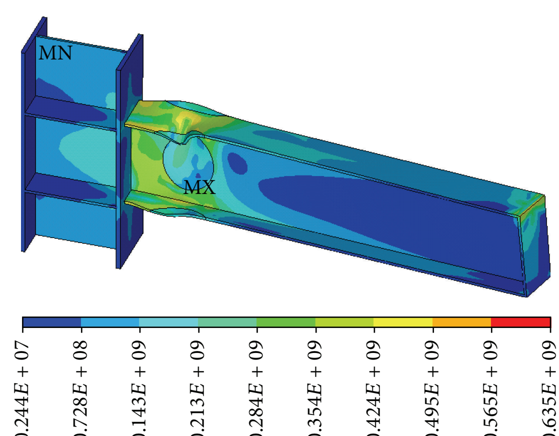


Figure 9: Stress of replaceable connection 2.

controlled by displacement and the loading increases by step from the initial state. The displacement increment of each level is 12 mm, two cycles are carried out for each level, and 12 levels are finally applied until the member damage with severe buckling or obvious deformation. The equivalent stress contours of the different connections when the displacement of the beam end reaches 144 mm are shown in Figures 7–10, respectively.

The above results show that the maximum stress of the traditional connection converges on the joint of the beam end and column when the ultimate displacement occurs; the plastic hinge generates on the beam end with apparent local buckling and it is inconvenient for repair after damage. The plastic hinge of the beam weakened connection offsets to the weakened zone but there exists serious local buckling in the weakened zone and total lateral deformation, so severe damage has occurred for the whole connection and the seismic capacity cannot meet the requirements.

The deformation of the replaceable connection 2 is similar to the traditional connection but the plastic hinge moves to the replaceable metal zone, and the local buckling and energy dissipation occur mainly in the low yield point metals while the damage in the main material is minor. It is credible that the capacity of the connection will be restored after the damaged low yield point metal is replaced.

The deformation of replaceable connection 4 with alloy Zn-22Al is similar to the connection with LY160 steel; the plastic hinge also moves to the replaceable zone, but as the yield strength of alloy Zn-22Al is lower, the yield deformation occurs in earlier load stage and the alloy part will buckle at the subsequent load stages. The buckling area will gradually scale

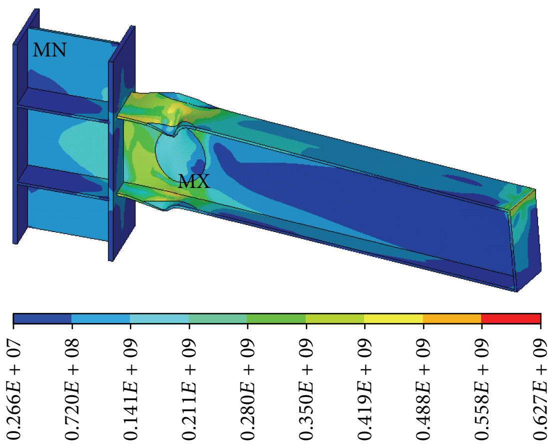


Figure 10: Stress of replaceable connection 4.

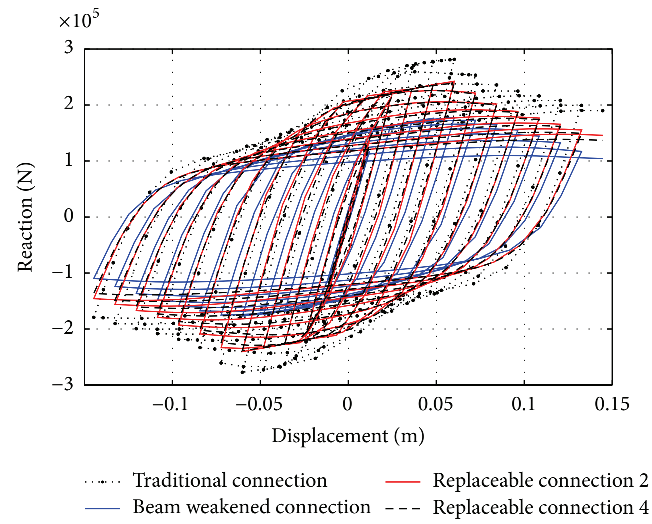


Figure 11: Hysteresis curves of different connections.

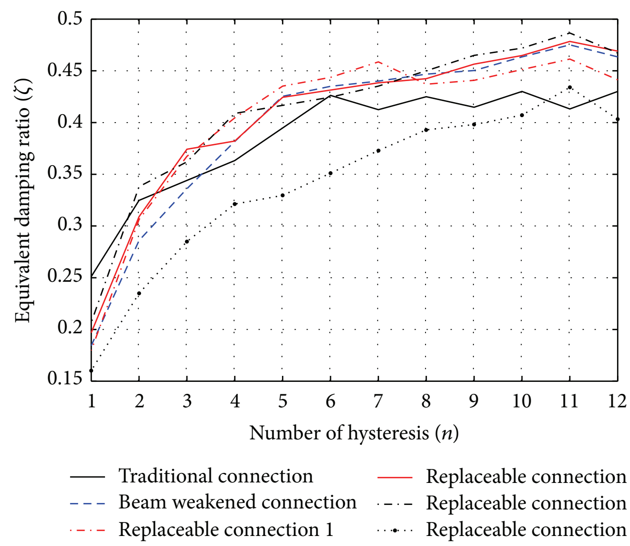


Figure 12: Equivalent damping ratio of different connections.

out the expected replaceable zone and it is hard to replace the alloy after earthquake though the whole deformation and capacity of the connection is guaranteed. Thus, it is not suitable to use the replaceable connection with alloy Zn-22Al for the steel structures in meizoseismal area.

The hysteresis curves of different connections are shown in Figure 11. It is apparent that the hysteresis loop of the replaceable connections and the traditional connection are fuller than the loop of the beam weakened connection. The bearing capacity of the beam weakened connection decreases rapidly in the last 5 cycles, and the capacity of energy dissipation is also insufficient. On behalf of comparing the energy dissipation capacity of different types of connections in detail, the assessment indices such as equivalent hysteretic damping ratio and Park-Ang damage index are used to evaluate the performance of different connections under cycle loading [25].

The equivalent hysteretic damping ratio ξ can be calculated according to the following formula:

$$\xi = \frac{E_D}{4\pi E_S}, \tag{1}$$

where E_D is the damping energy dissipated in one cyclic loading and equals the area of the corresponding hysteresis loop, and E_S is the maximum strain energy.

The Park-Ang damage index DI can be calculated according to the following formula:

$$\mathrm{DI} = \frac{x_m}{x_{cu}} + \beta \frac{E_h}{F_y x_{cu}}, \tag{2}$$

where x_{cu} is the limit displacement of members under monotonous loading, F_y is the yield strength of members, x_m and E_h are the actual seismic maximum deformation and cumulative hysteretic energy dissipation, and β is the energy dissipation factor of member, taken as 0.15 in this study.

The curves of equivalent hysteretic damping ratio of different connections are shown in Figure 12 and the damage curves of Park-Ang of different connections are shown in Figure 13. It can be seen from the figures that the equivalent hysteretic damping ratio of traditional connection increases slowly and keeps stable in large deformation stage, but the Park-Ang index increases rapidly. The results indicate that the energy dissipation capacity and ductility of the traditional connection are insufficient and the accumulated damage is severe.

Although the equivalent hysteretic damping ratio of the weakened connection is much larger than the traditional connection and the later values reach 0.45, the Park-Ang index history demonstrates that the damage of the weakened connection suffers the most serious damage and the premature local buckling induces the loss of carrying capacity.

The equivalent hysteretic damping ratios of the replaceable connection 2 are similar to the values of the weakened connection, having superior energy dissipation capacity.

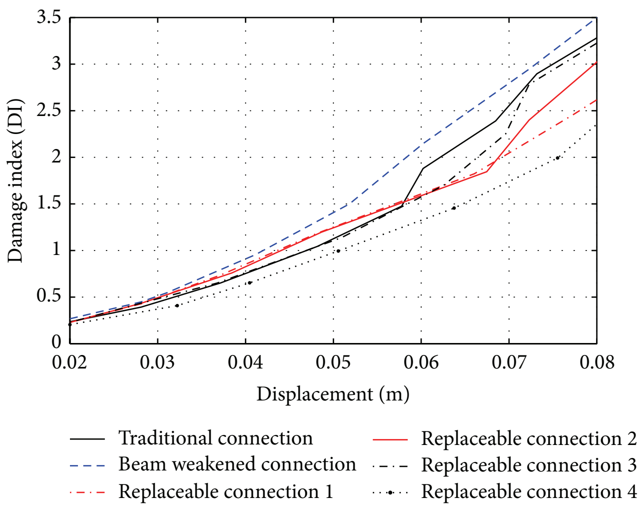


FIGURE 13: Damage index of different connections.

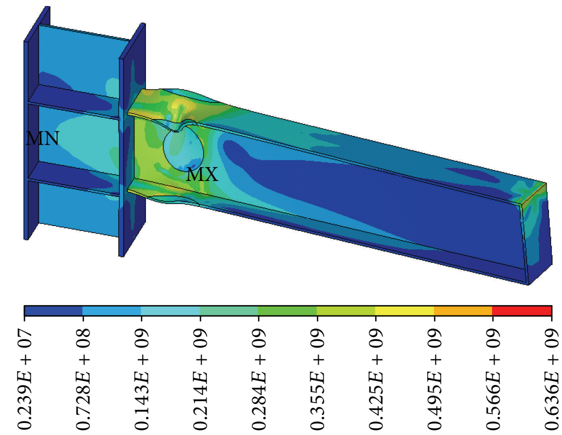


FIGURE 14: Stress of replaceable connection 1.

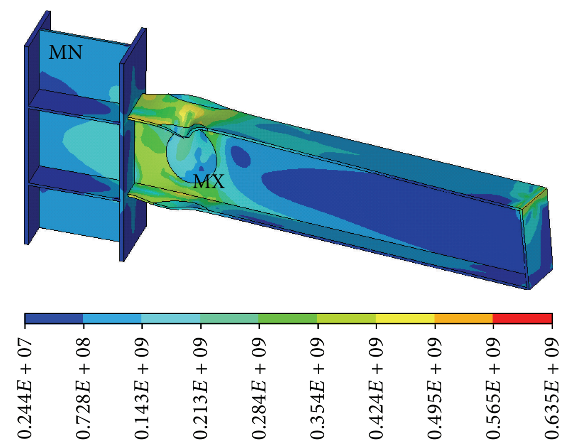


FIGURE 15: Stress of replaceable connection 2.

Furthermore, the damage index is less and increases slowly, especially in the large deformation stages. The results above prove that the low yield point steel firstly yields and dissipates energy sufficiently and the damage degree keeps slight even in large deformation due to the excellent extensibility of the low yield point steel.

The equivalent hysteretic damping ratios and Park-Ang damage index of the replaceable connection 4 are obviously low, indicating the insufficient energy dissipation capacity, and the damage degree is serious. It is proved that the alloy cannot constantly dissipate energy for its excessive low yield point though it has high extensibility. The destruction of the connection is more and more serious in the large deformation stage.

In summary, the replaceable connection with LY160 has better ductility and energy dissipation capacity than the traditional connection; the plastic hinge moves from the center zone to the beam to avoid the brittle fracture failure. Moreover, the inelastic deformation occurs in the low yield point metal and the damage in main steel is controlled. In addition, the low yield point metal can be replaced after main earthquake or buckling deformation to prevent structural damage under aftershocks.

In order to compare the influence of different replaceable sizes on the connection performance, three types of replaceable beam-column connections are applied on cyclical static load, and the results are shown in Figures 14–16. When the inelastic deformation occurred on the beam end, the local buckling arises in the replacement zones of all the connections and the bearing capacities are nearly identical, and the hysteresis curves of the replaceable connections with different sizes are shown in Figure 17. The results show that all the hysteresis curves have plump shapes and satisfactory ductility, and the size of the replaceable parts has less impact on the energy dissipation capacity of the connections. Therefore, the replaceable connection 2 which has middle size will be used in the later study.

5. Seismic Analysis of Steel Frame Based on Multiscale Modeling

In order to study the dynamic performance of steel frame with different types of connections under earthquake, one steel frame with two stories is analyzed by inelastic time-history method with finite element analysis software ANSYS. The detailed size of the structure is shown in Figure 18. The axial-load ratio of the column is 0.30 and the additional mass is 1.6 t for each story. Since the computational efficiency of the structure build-up with solid elements is low, the multiscale model is also studied. In the solid model, SOLID95 element is adopted for both columns and beams. In the multiscale model, beam-column connections are built with SOLID95 element and other parts are built with beam element BEAM188, and the actual connections between different types of elements are simulated by establishing constraint equations and defining rigid connections, so the accuracy is assured.

On behalf of verifying the accuracy of the multiscale model, the monotonic loading controlled with displacement is firstly applied on the models, and the ultimate load displacement is 48 mm. The nodal force and the displacement

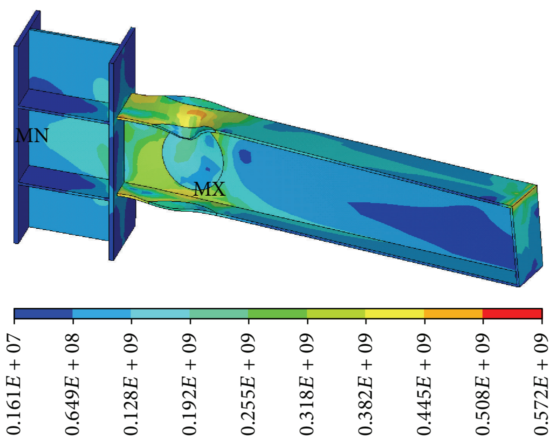


FIGURE 16: Stress of replaceable connection 3.

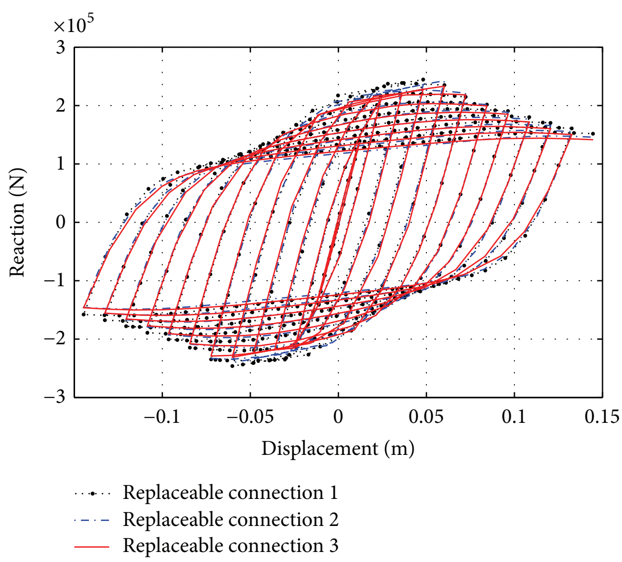


FIGURE 17: Hysteresis curve of different connections.

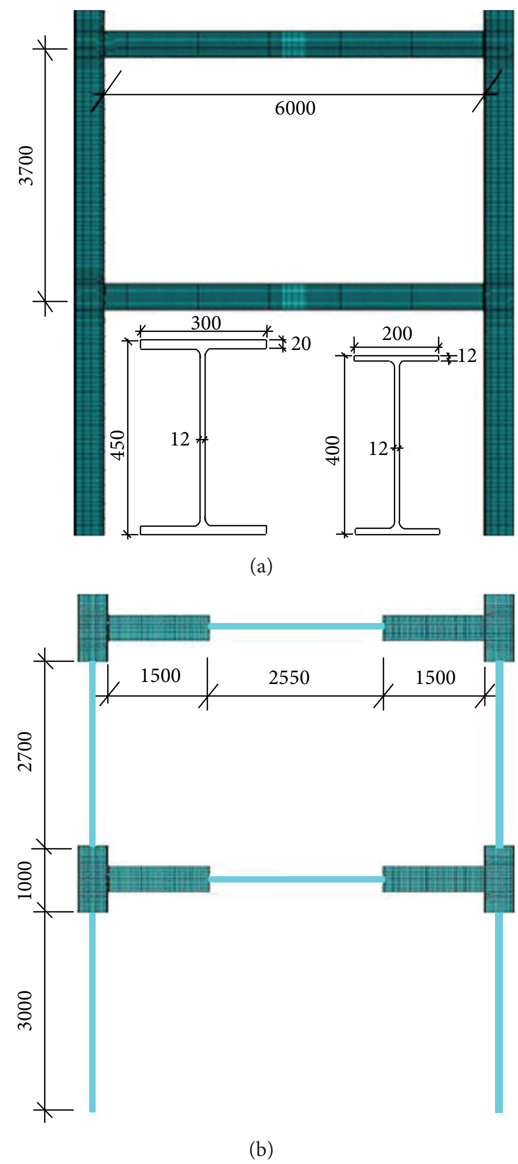


FIGURE 18: (a) All solids models and section size and (b) multiscale models and section size.

response of the top floor in different models are shown in Figure 19. It can be seen that the error of the multiscale model is less than 5% and the accuracy is acceptable. In seismic analysis, El Centro waves are selected as the ground motion input, and the peak acceleration amplitude is adjusted to 7.0 m/s^2, and the duration is taken as 16 s. In the same grid scale division accuracy, the displacement history of the top floor in the solid model and the multiscale model is shown in Figure 20, and the results are approximate.

The comparison indicates that the accuracy of static and dynamic analysis can be obtained by both multiscale model and solid model. However, the computing time for the solid model seismic analysis is 3417 min and only 1512 min for the multiscale model; thus, the advantages of the multiscale model are obvious.

In time-history analysis, the local stress contours of the first floor of the frames with different connections are shown in Figures 21–24. It can be seen that stress of frame with traditional connection reaches maximum value in beam-column joint. In beam weakened connection, stress concentration occurred on the flange weakened zone and web plate hole, and the lateral buckling deformation appears. The stress distribution of the replaceable connections 2 and 4 is nearly uniform and the stress of connection core zone effectively decreases, which is beneficial to resist rare earthquake.

The displacement histories of top floor of different frames are shown in Figure 25. The value of the frame with weakened connection has maximum which reaches 0.028 m and the extreme value of the traditional frame and the replaceable frame both are 0.020 m. In general, the displacement and the maximum stress values are all maximal in the frame with weakened connections, and the behavior distinction of the frames with traditional connections and replaceable connections is not obvious. However, the frame with

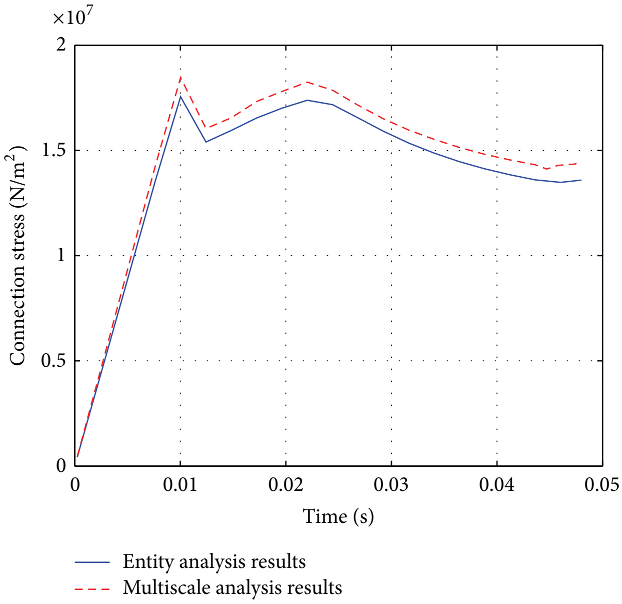


FIGURE 19: Stress-strain curve of top connection.

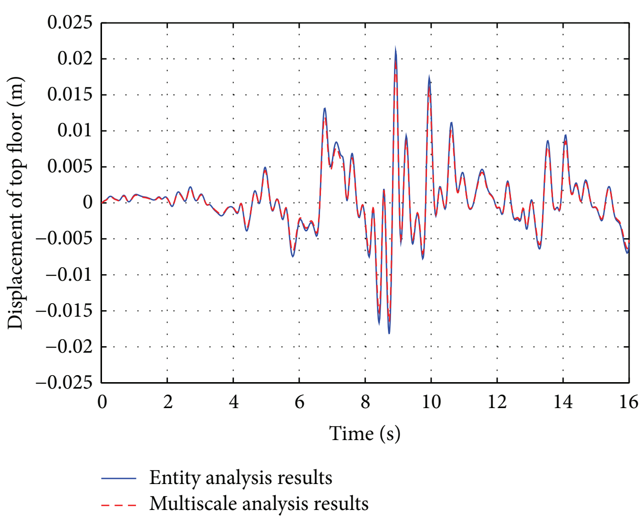


FIGURE 20: Displacement history of top floor.

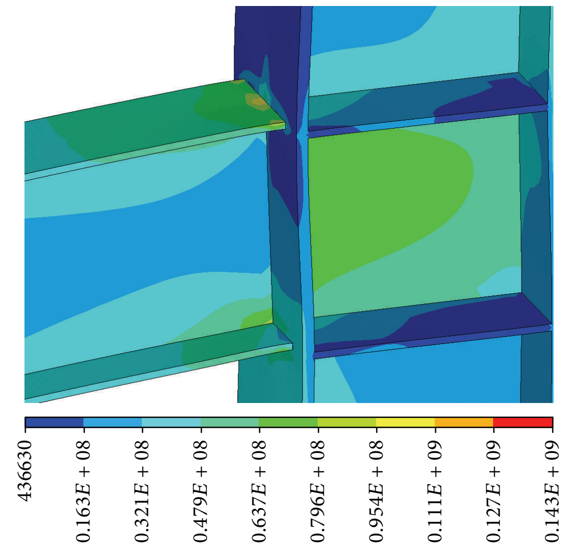


FIGURE 21: Stress of frame with traditional connection.

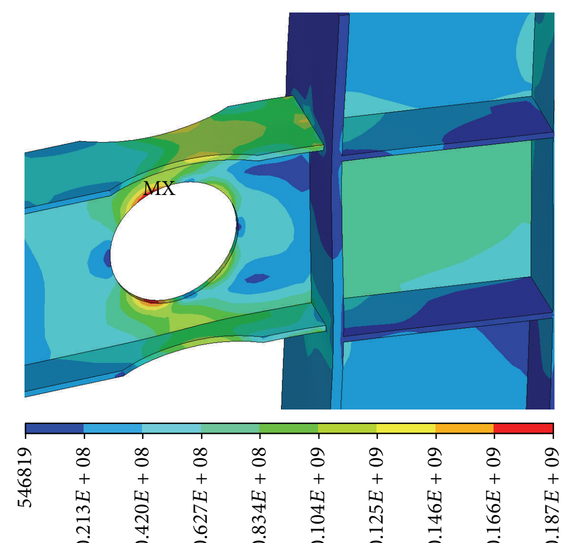


FIGURE 22: Stress of frame with weakened connection.

replaceable connections has better emergency capacity and resilient ability after strong earthquake, so it is suitable to be promoted and applied in steel structural engineering. It should be emphasized that the application of the connections with Zn-22Al should be strictly considered especially in rare earthquake because the damping capacity is not stable on occasion.

6. Conclusion

The beam weakened connection can shift the plastic hinge away from the beam end and dissipates energy sufficiently when it is subjected to earthquake, so the ductility design can be realized partially. However, the local buckling and lateral shift will occur and the insufficient safety is the deficiency; the repairs after earthquake are also difficult.

The replaceable steel connection with low yield point metal is proposed in order to avoid the disadvantages in the weakened connection. The low yield point metal in the flange slab and web plate firstly yields and adequately dissipates energy in earthquake, so the performance of the overall connection and frame is improved. In addition, the yield point metal can be replaced quickly and efficiently after the earthquake, and the idea of resilient structure is embodied.

In this study, the low yield point steel LY160 and composition metal Zn-22Al is proposed to be used as the replaceable metal. The constitutive relationships of different metals are obtained by performance test. The seismic performances of the three types of connections which include traditional connection, beam end weakened connection, and replaceable

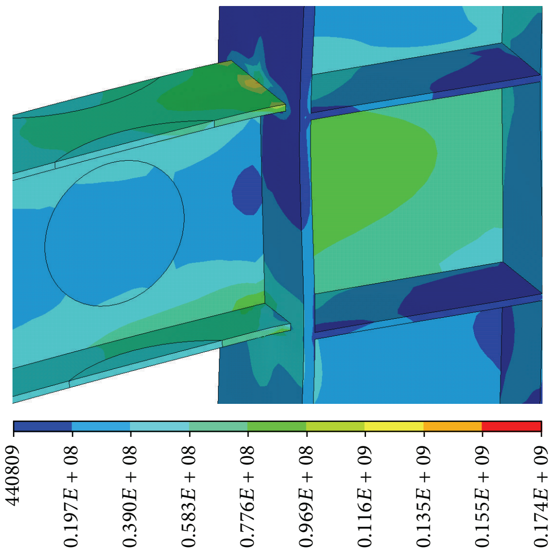


FIGURE 23: Stress of frame with replaceable connection 2.

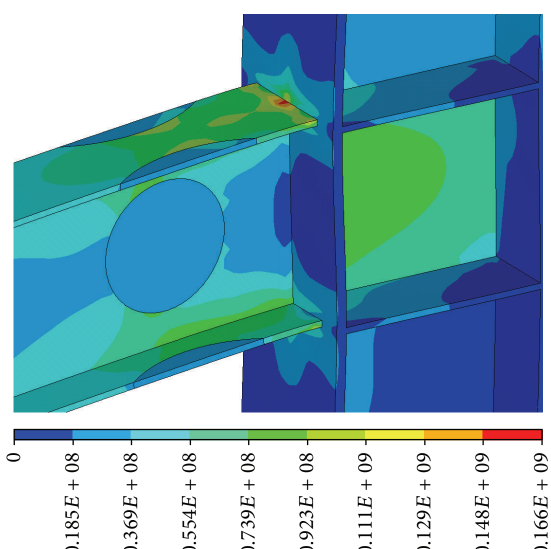


FIGURE 24: Stress of frame with replaceable connection 4.

connections are studied using FEM. The results show that the replaceable connection with LY160 has superior and stable energy dissipation capacity, avoiding the local buckling and lateral deformation which might occur in the beam weakened connections, and the replaceable connection is convenient to be replaced and reconstituted. The replaceable connection with Zn-22Al has moderate dissipation capacity in small and medium earthquake but it is not advised to be used in high-rise steel structures or structures in meizoseismal area.

For comparing and analyzing the damping capacity of the whole structures, the finite element models of steel frame with different types of connections are established based on multiscale method and are analyzed by inelastic time-history method. The analysis results approve that the displacement of steel frame with replaceable type beam-column connection is reduced, and the performance of the main structure is

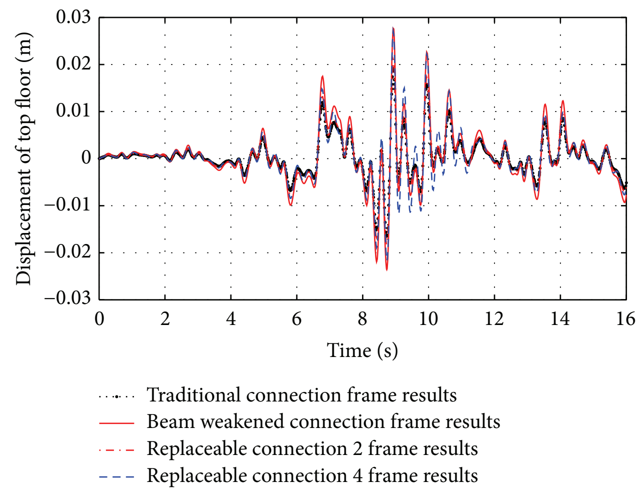


FIGURE 25: Displacement history of top floor.

enhanced and the energy is effectively dissipated by the low yield point metals. Furthermore, the damaged connections with low yield point steel can be easily repaired after the main earthquake, which ensure the realization of the resilient structures. Compared with the solid model, the multiscale finite element model can simulate the stress state of connections and dynamic response of the overall structures, nearly having the same accuracy, but the computational efficiency is improved evidently. It is suitable to use multiscale finite element model for steel structure design and analysis.

At present, the construction details, the design method, and the maintenance technology of the replaceable connection still need improvement, and more intensive analysis and experiments are required in further studies.

Conflict of Interests

The authors of the paper declare that they have no financial and personal relationships with other people or organizations that can inappropriately influence their work; there is no professional or other personal interests of any nature or kind in any product, service, and/or company that could be construed as influencing the position presented in, or the review of, the paper.

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